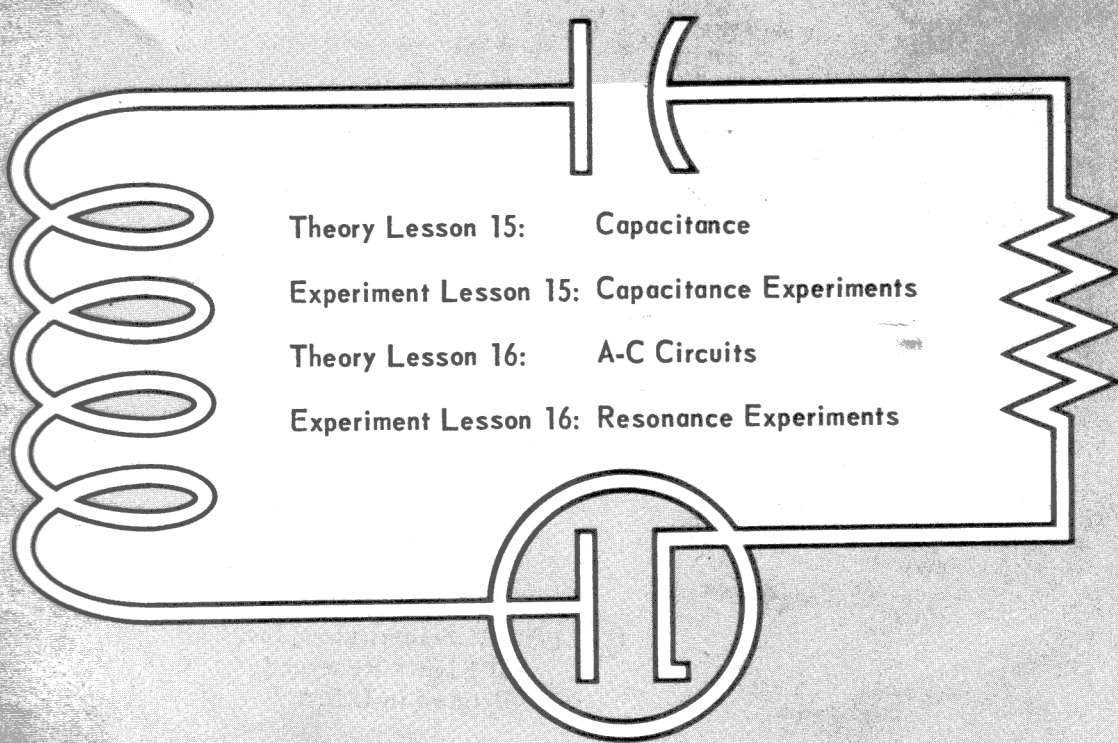


ELECTRONIC FUNDAMENTALS



Theory Lesson 15: Capacitance
Experiment Lesson 15: Capacitance Experiments
Theory Lesson 16: A-C Circuits
Experiment Lesson 16: Resonance Experiments

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New York, N. Y.



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ELECTRONIC FUNDAMENTALS

THEORY LESSON 15

CAPACITANCE

- 15-1. Charging A Capacitor in A Vacuum
- 15-2. Current Flow In Capacitors
- 15-3. Measurement
- 15-4. Dielectric Action
- 15-5. Factors Affecting Capacity
- 15-6. Capacitor Losses
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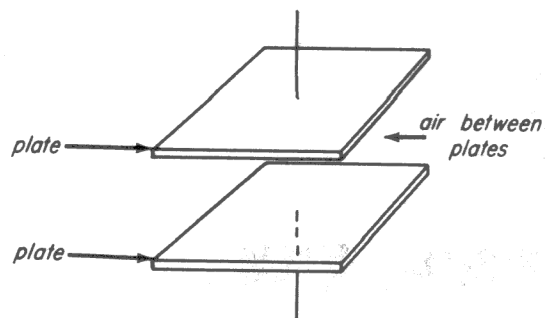
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Theory Lesson 15

INTRODUCTION

In earlier lessons you learned about two basic properties of electric circuits, resistance and inductance. In this lesson, you will study the third basic circuit property, known as *capacitance*. Capacitance is defined as the property of a circuit that opposes any change of voltage in the circuit. (You recall that inductance opposes any change of *current*.) Capacitance is also defined as the property that makes it possible to store electricity between two conductors, insulated from each other, when a potential difference exists between them. Capacitance appears in all kinds of electrical and electronic circuits. Without it, radio and television, as we know them today, could not exist. In the pages that follow, we will take these definitions apart and see exactly how capacitance affects various circuits.

A part that is specially made to possess the property of capacitance in a circuit is called a *capacitor*. Some old-time radio engineers, servicemen, and parts dealers call a capacitor a condenser, but the term capacitor is more accurate and is rapidly becoming popular so it will be used in these lessons.



a simple capacitor

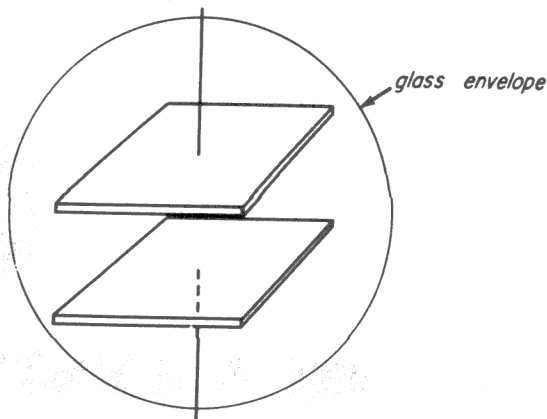
Fig. 15-1

The simple capacitor is made from two conductors, called *plates*, that are separated from each other by an insulating material called a *dielectric* (nonconductor). Such a simple capacitor is shown in Fig. 15-1. The capacitor plates are shown separated from each other by the dielectric, which, in this case, is air. Practical capacitors, of the kind used in radio and television receivers, are shown and discussed later in this lesson. Now we will study capacitor action.

15-1. CHARGING A CAPACITOR IN A VACUUM

In order to understand the basic theory of a capacitor, let us place the two capacitor plates in a vacuum, as shown in Fig. 15-2. When a vacuum is the dielectric, the area surrounding the plates will be free of atoms. Therefore, we can concentrate our attention on the atoms of the plates and their connecting wires.

The atoms of a conducting material have some electrons that are held very loosely in their orbits and may be moved to other



a simple capacitor in a vacuum

Fig. 15-2

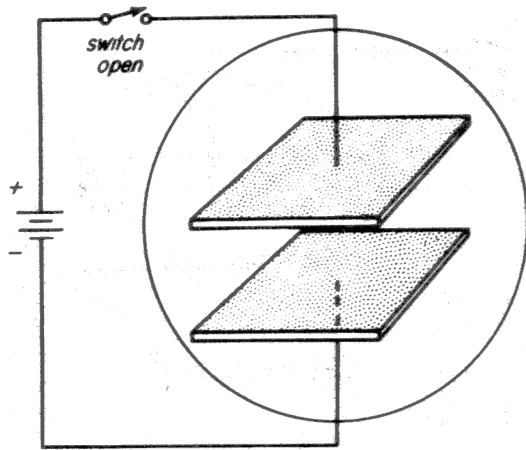


Fig. 15-3

atoms when a difference of potential is applied to the conductor. In a capacitor, if no difference of potential is applied, these electrons remain in their orbits, and the capacitor plates are electrically neutral. Since there are billions of atoms with their electrons in each plate, we can't show them all, but we can represent some of the loosely held electrons by dots. As the drawing in Fig. 15-3 shows, there are roughly the same number of loosely held electrons in each plate. Bear in mind, however, that there are protons as well as other electrons in the plates.

If we connect a battery across the capacitor, the potential difference of the battery will cause some of the loosely held electrons to move from atom to atom. This action continues all the way around the circuit from one capacitor plate, through the connecting wires and the battery, to the other plate. Let's look at this action one step at a time so that we can see exactly what happens.

In Fig. 15-3 we see the simple capacitor in a vacuum with a battery connected across the plates. Notice that the positive terminal of the battery is connected to a switch and then to the upper plate of the capacitor, while the negative terminal of the battery is connected to the lower plate. As long as the switch is open, the battery voltage cannot appear across the capacitor and the plates remain electrically neutral. However, when we close the switch, the positive terminal of the battery will be connected to the upper

plate. The positive charge of the battery will attract some of the loosely held electrons in the upper plate, and they will move to other atoms in the direction of the positive battery terminal. These electrons move only from one atom to the next. For each electron that has moved into a new atom, another electron leaves that atom and travels to still another. Since electrons are leaving the upper plate, the upper plate starts to have more protons than it has electrons and, therefore, is becoming positively charged.

While the positive terminal of the battery is attracting electrons, the negative terminal is repelling them. So, some of the loosely held electrons in the wire between the battery and the lower plate of the capacitor will be forced out of their atoms and will move into atoms farther away from the battery, toward the lower plate. As a result, some of the electrons move into the lower plate and stay there because there is nowhere else for them to go. Because the lower plate of the capacitor is getting more electrons than it has protons, it is becoming negatively charged, as shown in Fig. 15-4. This action continues, with more and more electrons leaving the upper plate and piling up on the lower plate, until the difference in potential between the upper and lower plates is equal to the battery voltage. When the capacitor voltage equals the applied voltage, we say that the capacitor is fully charged. The charge on each capacitor plate has the same

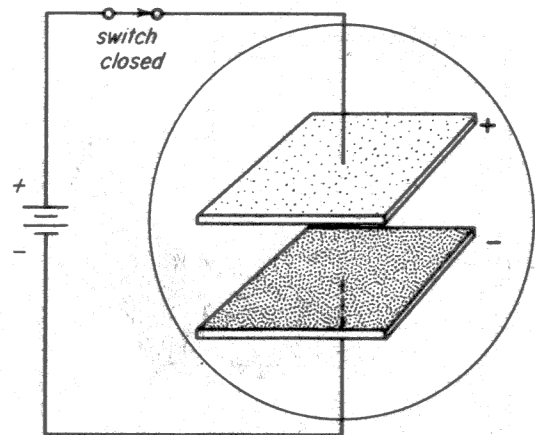


Fig. 15-4

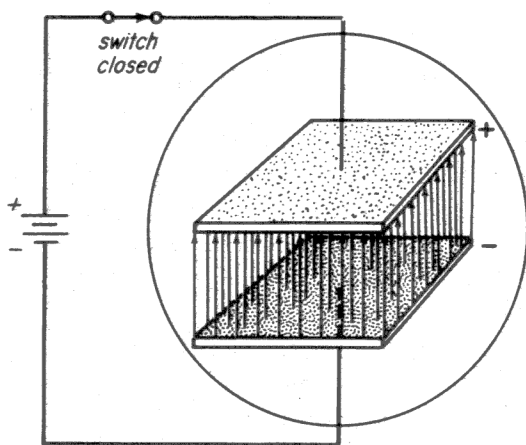


Fig. 15-5

polarity as the battery terminal to which it is connected. We can mark the capacitor plates with + and - signs, as shown in Fig. 15-4, to show the polarity of charge.

While some capacitors are *polarized* (meaning that they have positive and negative plates that cannot be reversed), most capacitors have no fixed polarity. So if we had originally connected the battery so that the negative terminal was connected to the upper plate and the positive terminal to the lower plate, the polarity of the capacitor would also be reversed. Capacitors, then, acquire the same polarity as the source of potential difference to which they are connected. This polarity exists only as long as the capacitor remains charged.

You learned in Theory Lesson 4 that electrostatic lines of force radiate out from any charged body. Figure 15-5 shows the

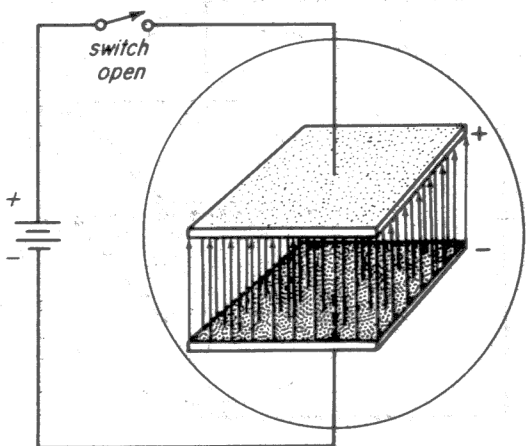


Fig. 15-6

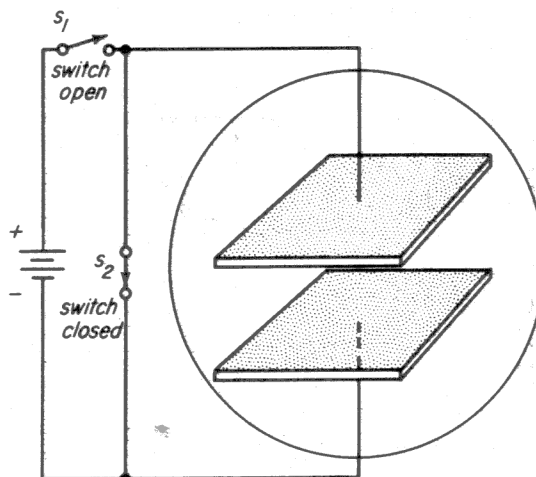


Fig. 15-7

electrostatic field that exists between two oppositely charged plates of a capacitor. The field consists of lines of force that leave the negatively charged plate at right angles to its surface and enter the positively charged plate at right angles to its surface. The lines are shown to have direction by being marked with arrows. Sometimes these are drawn showing the arrows pointing the other way to agree with the old-fashioned theory that current flows from positive to negative. However, the lines of force drawn in Fig. 15-5, represent the force that would act upon a free electron that entered the field, and the arrows show the direction in which the lines of force would tend to cause the electron to move.

The field that exists between the plates of the charged capacitor, as shown in Fig. 15-5, is called the electrostatic or the electric field and exists as long as the plates are charged and disappears when the plates become neutral. The field is also referred to as the dielectric field.

Now that we have charged the capacitor inside the vacuum, let's see what happens when we disconnect the battery in the circuit of Fig. 15-6. With the switch open, there is no electrical connection between the upper and lower plates, and, therefore, no path for electrons to travel along. For this reason, the excess electrons that were forced into the lower plate must remain there. The upper plate is not connected to a circuit, and

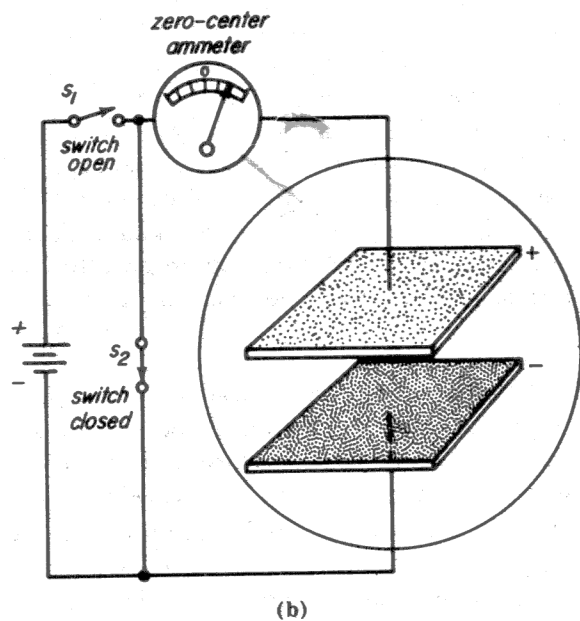
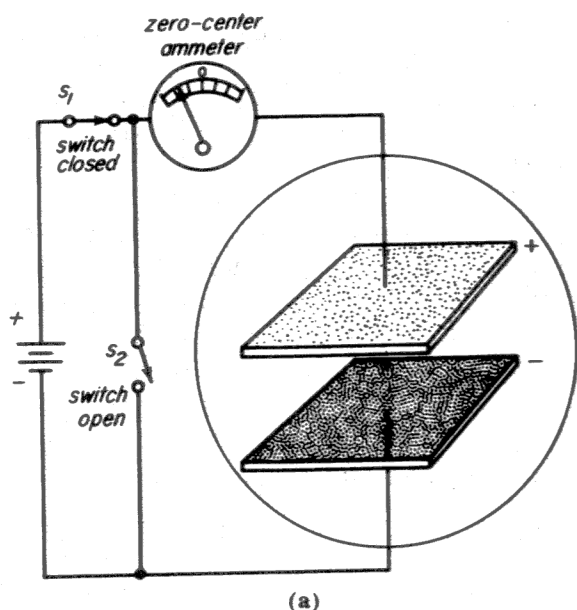


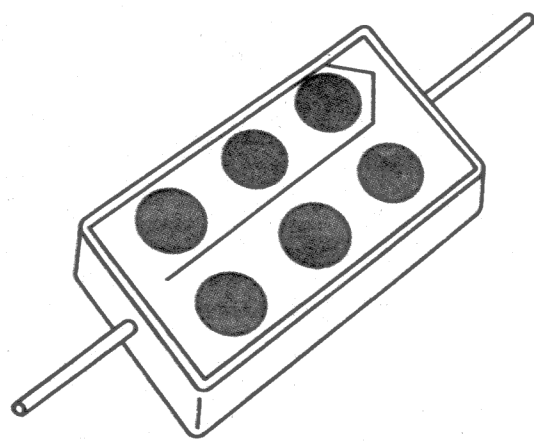
Fig. 15-8

no electrons can reach it. Therefore, the charge remains on the capacitor after the battery is disconnected. This is a very important point to remember about capacitors. High-grade capacitors can hold a charge for days at a time. A capacitor in a radio or television receiver may be disconnected from any source of electric power and still be fully charged. If you were to touch the terminals of such a capacitor while testing the receiver, you would receive a shock. That is why careful servicemen take no chances with capacitors. Instead, they discharge them before testing, by connecting the two terminals of the capacitor together.

Suppose we make the capacitor electrically neutral again. This can be done by closing switch S_2 in Fig. 15-7, which connects a wire from the upper plate to the lower plate. The excess electrons on the lower plate, attracted by the positive charge, travel toward the upper plate. This, in turn, will cause electrons in other atoms to move into the positive plate, and fill in the spaces left in the orbits of the atoms when the capacitor was charged. We can see, therefore, that each electron that leaves the lower plate will cause an electron to be added to the upper plate. When the excess electrons have left the lower plate, the atoms in the upper plate will each have a normal amount of electrons. The capacitor is then electrically neutral and is said to be *discharged*. When a capacitor is discharged, there is no longer any charge on either plate, so the electric field that existed between the plates collapses, as in Fig. 15-7.

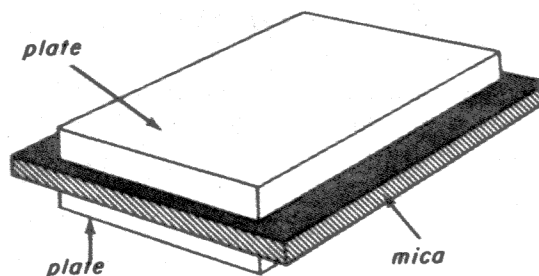
15-2. CURRENT FLOW IN CAPACITORS

Let's go back to the charging of a capacitor. When a difference of potential is applied to a capacitor, electrons are forced to move around the circuit. A movement of electrons around a circuit is a flow of electric current. Therefore, when a capacitor is being charged, a current actually flows in the circuit. This current flows for a very short time, just long enough for the capacitor to become charged. As soon as the capacitor is charged, the electrons stop moving and the current stops. We can show this by placing an ammeter with its zero calibration in the center of the scale (so it can show current flowing in either direction) in series with the circuit. Then, as we watch the meter needle we close switch S_1 (and leave switch S_2 open), as in Fig. 15-8a. Immediately, the needle will jump up scale in one direction and quickly return to zero, which will show that a current flows while the capacitor is being charged. Then, if we open switch S_1 and close switch S_2 , as in Fig. 15-8b, we will provide a discharge path through the meter. As soon as S_2 is closed, the meter needle will jump up-scale in a direction opposite to the charging



a mica capacitor

(a)



(b)

Fig. 15-9

direction and then will quickly return to zero, as the capacitor becomes discharged. So, while no current flows directly from plate to plate through the dielectric, current does flow in the circuit outside the capacitor as it charges and discharges.

15-3. MEASUREMENT

Capacitance. A capacitor placed in an electric circuit will store a charge when voltage is applied to its plates. The amount of charge depends, in part, upon the area of the capacitor plates. The measure of the capacitance of a capacitor is called its *capacity*. Capacity is measured in units called *farads*. A capacitor is said to have a capacity of one farad if one volt causes it to store one coulomb of electricity. The farad is much too large a unit for measuring practical capacitors used in radio and television circuits, so normally we use a unit called the microfarad, abbreviated mf or μf , which amounts to one-millionth of a farad. For

some circuits, even this unit is too large, so a smaller unit, equal to one millionth of a millionth of a farad is used. This unit is called the micromicrofarad, and is abbreviated mmf or $\mu\mu\text{f}$.

For convenience, in converting these units from one to the other the following table has been set up. Notice that the conversions are made using powers of ten.

$$1 \text{ farad} = 10^6 \mu\text{f} = 10^{12} \mu\mu\text{f}$$

$$1 \mu\text{f} = 10^{-6} \text{ farads} = 10^6 \mu\mu\text{f}$$

$$1 \mu\mu\text{f} = 10^{-12} \text{ farads} = 10^{-6} \mu\text{f}$$

For example: $0.1 \text{ farad} = 10^5 \mu\text{f}$ or $10^{11} \mu\mu\text{f}$, $500 \mu\text{f} = 0.0005 \text{ farad}$ or $5 \times 10^8 \mu\mu\text{f}$, and $100 \mu\mu\text{f} = 0.0000000001 \text{ farad}$ or $0.0001 \mu\text{f}$. Other examples of converting from one unit to another will appear later in this lesson. While practical capacitors are measured in the smaller units, most calculations call for capacity to be expressed in farads. Therefore, it is important that you be able to convert one unit to the other without error.

Charge. Since the charge on a capacitor is produced by the movement of electrons in the circuit, we can measure charge just as we would measure such a movement. As an example, if 6.24×10^{18} electrons are removed from one plate of a capacitor, and the same number of electrons is added to the other plate, 1 coulomb of electricity has been moved around the circuit and 1 coulomb of electricity is stored in the capacitor.

Applying higher voltages to a capacitor will cause additional electrons to leave the positive plate and travel toward the negative plate. The more electrons we remove from the positive plate, the greater the charge that is stored in the capacitor. A lesser voltage on the plates of a capacitor causes fewer free electrons to leave the positive plate and go to the negative plate, which reduces the charge stored in the capacitor. A capacitor having more capacity than another will store a greater charge than the

smaller capacitor. This is because there are more loosely held electrons in their plates of large capacitors. Therefore, the charge on a capacitor depends directly on the capacity and the applied voltage.

There is a definite relation between the capacity of a capacitor, the voltage applied across its plates, and the charge that it can hold. This is shown in the equation below:

$$Q = C \times E$$

where:

Q = charge in coulombs

C = capacity in farads

E = the emf applied across the capacitor, in volts.

Suppose we try a sample problem to see how the equation is used. Let's assume we have a capacitor with a capacity of 1 microfarad connected across a battery having an emf of 10 volts. What is the charge on the capacitor? Starting with the equation, we can substitute values, remembering that the capacity must be converted from microfarads to farads so that the capacity actually is 0.000001 farads, or 1×10^{-6} farads.

$$\begin{aligned} Q &= C \times E \\ &= 1.0 \times 10^{-6} \times 10 \\ &= 1 \times 10^{-5} = 0.00001 \text{ coulomb} \end{aligned}$$

We can turn the same equation around in order to calculate the capacity in terms of the amount of charge, Q , and the voltage E , as:

$$C = \frac{Q}{E}$$

For example, a capacitor connected across a 100-volt d-c source shows a charge of 0.01 coulomb. Then:

$$C = \frac{Q}{E}$$

$$= \frac{0.01}{100}$$

$$= 0.0001 \text{ farad} = 100 \mu\text{f}$$

Let's see what happens when the charge remains the same and the voltage increases. Let $Q = 0.01$ coulomb (as it did before) and $E = 500$ volts.

Then:

$$C = \frac{Q}{E}$$

$$= \frac{0.01}{500}$$

$$= 0.00002 \text{ farad} = 20 \mu\text{f}$$

Now let's increase the charge and keep the voltage the same as it was. Let $E = 100$ volts (as it was in the first example) and $Q = 0.5$ coulomb.

Then:

$$C = \frac{Q}{E}$$

$$= \frac{0.5}{100}$$

$$= 0.005 \text{ farad} = 5,000 \mu\text{f}$$

Don't let these figures lead you into thinking that you can vary the capacity of a capacitor by decreasing the voltage or increasing the charge. Actually, the capacity for any particular capacitor is fixed, so a 10- μf capacitor remains a 10- μf capacitor, even if the applied voltage is reduced. However, if the voltage and amount of charge are known, the capacity may be calculated. For any capacitor, when the voltage increases the charge increases, and when the voltage decreases, the charge decreases.

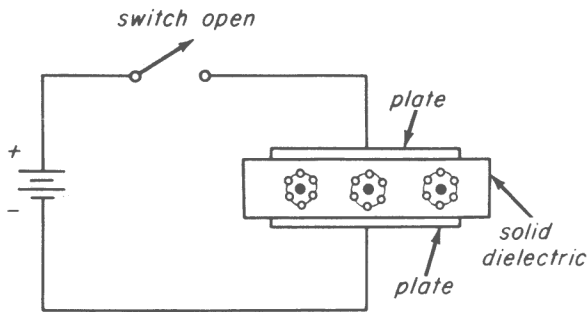


Fig. 15-10

15-4. DIELECTRIC ACTION

The capacitor we used in discussing charging and discharging is known as a *vacuum capacitor*. While capacitors of this type are sometimes used in transmitters, practical capacitors for use in radio receivers and other electronic equipment are usually made from two or more conducting plates separated by a nonconductor, or insulator, which, as you know, is called a *dielectric*. For example, a capacitor using mica as a dielectric is shown in Fig. 15-9a and b. Other dielectric materials often used are air, paper, oil, and ceramics. Practical capacitors are normally described by naming the dielectric material, such as *paper capacitor* or *mica capacitor*. When you see such a description, remember that it refers to the dielectric only.

A capacitor that has a dielectric made of mica or paper has a much greater capacity than the same capacitor would have if a vacuum were the dielectric. The increased capacity is due to the action in the dielectric when the capacitor is being charged. In charging this kind of capacitor, the atoms of the dielectric are affected by the difference of potential across the capacitor plates. This is the second of the two actions we said took place in a capacitor being charged.

Let's see what happens when a capacitor with a solid dielectric is charged. In Fig. 15-10, we see such a capacitor. Notice that only three of the atoms of the dielectric material are shown. Notice, too, that six electrons are shown in each orbit. The drawings show us that what occurs in these atoms takes place in the atoms of whatever dielectric material is used.

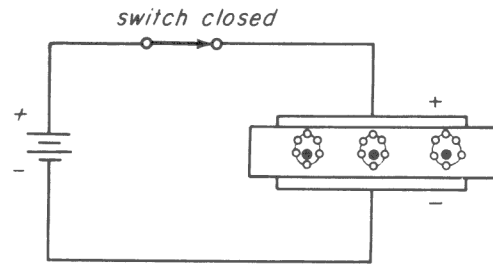
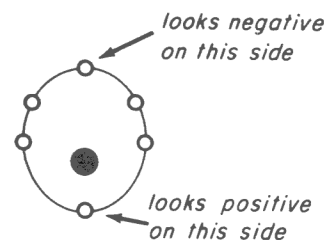


Fig. 15-11

We know that when the switch is closed, electrons will move around the circuit and cause a positive charge to appear on one plate and a negative charge on the other plate. The electrons in the orbits of each dielectric atom, being negative, will be attracted toward the positively charged plate, while the positively charged nucleus will be attracted toward the negatively charged plate, as shown in Fig. 15-11. Of course, the electrons still remain in their orbits because the dielectric is an insulator; in an insulating material, the electrons are tightly bound to their atoms, so are not free to leave them. However, the attraction of the dielectric electrons toward the positively charged plate causes the orbits of the electrons in the dielectric atoms to change shape. With its electrons straining toward the positively charged plate and the nucleus toward the negatively charged plate, each dielectric atom acts like a positive charge on the side facing the negatively charged plate and a negative charge on the side facing the positively charged plate, as shown in Fig. 15-12. Because all of the dielectric atoms are strained in the same way and in the same direction, the dielectric acts like a charged body with its own electric field. This field has a direction that is opposite to that set up by the charged capacitor plates and so cancels out some of the lines of force set



dielectric atom with strained orbit

Fig. 15-12

up by the charged capacitor plates. This causes more electrons to be repelled from the upper (positively charged) plate and to be attracted to the lower (negatively charged) plate, until the electric field in the capacitor again reaches its normal strength. As you can see, the major effect of the dielectric material is to increase the charge on the capacitor plates over the amount of charge that would exist on the same plates placed in a vacuum.

15.5. FACTORS AFFECTING CAPACITY

We have already seen that the capacity of a capacitor may be found by using the formula

$$C = \frac{Q}{E}$$

By experimenting, it has been found that the amount of charge increases with the area of the capacitor plates. It has also been found that the greater the distance between the plates, the greater the emf necessary to set up a charge between them. Therefore, the formula for the capacity of two parallel flat plates in a vacuum may be written:

$$C = \frac{A}{d}$$

where:

A = the area of one flat side of one plate

d = the distance between plates

To make this formula useful in finding the values of capacity in microfarads when the area is given in square inches and the distance in inches, we add a conversion factor and write it thus

$$C = 22.45 \times 10^{-8} \frac{A}{d}$$

where:

C = capacity in microfarads

A = area of one flat side of one plate
in square inches

d = distance in inches

However, we know that the capacity for storing a charge increases when the capacitor plates are taken out of the vacuum and separated by some other dielectric. For example, when clear India mica is used as the dielectric, the capacity is increased to seven times what it is when the dielectric was a vacuum.

When we compare materials used as dielectrics, we use a vacuum as a standard. For instance, we can say that clear India mica is seven times better than a vacuum when used as a dielectric. The measure of how much better one material is than another when used as a dielectric is called the *dielectric constant* of the material. Because we use a vacuum as our standard, we say that it has a dielectric constant of 1. Table A shows the dielectric constants for several dielectric materials. In this table, air is shown to have a constant (abbreviated k) of 1.00059, but for all practical purposes, it is the same as for a vacuum. Porcelain is shown to have a k of 5.5, which means that it is 5.5 times better than a vacuum (or air) when used as a dielectric.

TABLE A - DIELECTRIC CONSTANTS

Material	Dielectric Constant
Air	1.00059
Castor Oil	4.7
Glass (common)	4.2
Flint	7
Mica (clear India)	7
Paper	2 to 3.4
Porcelain	5.5
Quartz	4.5
Vacuum	1.0
Water (distilled)	81

To find the capacity of capacitors using dielectric other than vacuum, we must figure in the dielectric constant. Then the formula becomes:

$$C = 22.45 \times 10^{-8} \frac{kA}{t}$$

where:

A = the area of one flat side of one plate in square inches

k = the dielectric constant

t = the thickness of the dielectric

This formula applies to all capacitors made from two parallel plates, no matter what dielectric is used. Note that t , thickness of the dielectric, is the same as d , the distance between the plates, when both plates are firmly held against the dielectric.

Let's try using the formula, to see how it works. Suppose two parallel plates each of four square inches in area are placed 1/10-inch apart in a vacuum. We find the capacity, C , in this manner.

$$\begin{aligned} C &= 22.45 \times 10^{-8} \frac{kA}{t} \\ &= \frac{22.45 \times 10^{-8} \times 1 \times 4}{0.1} \\ &= \frac{89.80 \times 10^{-8}}{10^{-1}} \\ &= 89.8 \times 10^{-7} \mu\text{f or } 8.98 \mu\text{f} \end{aligned}$$

However, if the dielectric were flint instead of a vacuum, the capacity would be $7 \times 8.98 \mu\text{f}$ or $62.86 \mu\text{f}$.

However, not all capacitors are made from just two parallel plates. Many mica capacitors are made by stacking sheets of metal foil and sheets of mica in alternate layers, as shown in Fig. 15-13. In calculating the capacity of 2-plate capacitors, we have been using the area of one flat side of one of the two plates. There were two reasons for doing this. Only the side of the

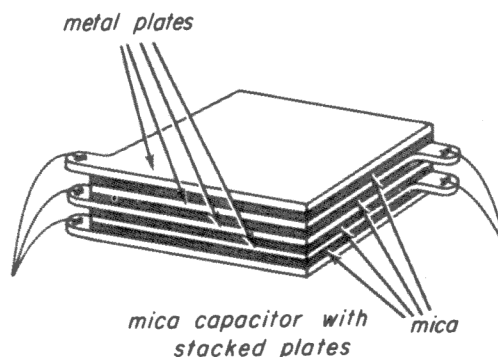


Fig. 15-13

plate that faces the dielectric and the other plate contributes to the capacity of the capacitor. The charge on one plate is equal and opposite the charge on the other plate, so only one plate is used in our calculations. However, when plates are stacked, as they are in Fig. 15-13, both sides of the inner plates must be considered when calculating the capacity. Figure 15-13 shows five plates in the capacitor. Of these, only one side of each of the outer plates adds to the capacity, while both sides of the three inner plates contribute to the capacity. All told, there are eight sides that are in use. That means that the capacity will be equal to the capacity of four 2-plate capacitors. To use the capacity formula to calculate the capacity of the capacitor in Fig. 15-13, we'd multiply the area of one plate-side by 4. The formula for multiple plate capacitors is the same as the one we've been using, except that it includes a factor that allows for capacitors of more than two parallel plates. It is written thusly:

$$C = \frac{22.45 \times 10^{-8} kA (N-1)}{t}$$

where:

C = capacity in microfarads

k = the dielectric constant

A = the area of one plate-side
(for each pair of plate-sides)

N = the number of parallel plates

t = the thickness of the dielectric

Let's apply this formula to our 5-plate capacitor. Let the number of plates (N) = 5; the area (A) of the plate-side is 4 square inches; the dielectric coefficient is 7; and the thickness of the dielectric is 0.1 inch. Then we find the capacity in this way:

$$\begin{aligned}
 C &= \frac{22.45 \times 10^{-8} \text{ kA } (N-1)}{t} \\
 &= \frac{22.45 \times 10^{-8} \times 7 \times 4 (5-1)}{0.1} \\
 &= \frac{22.45 \times 10^{-8} \times 7 \times 4 \times 4}{10^{-1}} \\
 &= 2514.4 \times 10^{-7} \text{ } \mu\text{f or } 251 \text{ } \mu\mu\text{f} \\
 &\quad \text{(approximately)}
 \end{aligned}$$

To summarize this section of the lesson, the three factors that affect the capacity of a capacitor are:

1. The area of the capacitor plates that face each other
2. The thickness of the dielectric
3. The kind of material used as the dielectric

15-6. CAPACITOR LOSSES

Leakage Current. Until now, we have thought of capacitors made from conducting plates separated by a dielectric that is a perfect insulator — one that permits no current flow. Earlier in this course, we learned that there is no such thing as a perfect insulator; therefore there is no perfect dielectric. So, current will flow from the negatively charged plate of the capacitor through the dielectric to the positively charged plate. This is called leakage current. When a dielectric material that has a very high resistance is used, this current may be so very low that, for all practical purposes, it may be ignored. Mica, glass, castor oil, and certain ceramic materials

are used as dielectrics because of their relatively low losses due to leakage.

Dielectric Losses. In Experiment Lesson 15, you will charge a capacitor, discharge it, and then measure the voltage across its terminals. If the experiment works out as it should, you'll find that some charge remains after the capacitor is apparently discharged. This is accounted for by the fact that the electron orbits of dielectric atoms are slow to return to their normal, neutral shapes; therefore, all of the excess electrons in the negatively charged plate are not repelled from that plate until some short time after the first effort to discharge the capacitor has been made. It is as if the dielectric absorbed some other charge, so it is called *dielectric absorption* loss. This absorption loss is greater when a.c. is applied to the capacitor plates and they are alternately charged in one direction and then the other, because the polarity changes so rapidly that the so-called absorbed charges cannot be released by the dielectric before the plate is charged in the opposite direction. In addition, the straining of the electron orbits during charging takes energy. When the applied voltage is d.c. or low-frequency a.c., practically no energy is used, but, as the frequency becomes higher and higher, more and more energy is needed to force the electron orbits to strain in the opposite direction each time the charging voltage changes direction. This energy, while never very great, is considered a loss and is called *dielectric hysteresis loss*.

Resistance Losses. The leads and connections of capacitors, including the conductors that make up the plates of the capacitor, offer some resistance (usually small) to the flow of current. Any power lost because of this resistance is called *resistance loss*.

In most high-grade capacitors operating in low-frequency a.c. circuits, these losses are so very small that they can be ignored. However, as the circuit frequency increases the losses become more important, and in very high frequencies they cannot be ignored.

15-7. DIELECTRIC BREAKDOWN

One problem that comes up in selecting a dielectric for a capacitor is the possibility of current arcing through the dielectric from one plate to the other. A very great voltage would be required to cause arcing when the dielectric is a vacuum. However, when other dielectrics are used, the dielectric orbits are strained out of shape. The higher the voltage on the plates, the greater is the strain on the dielectric atoms.

We can compare this action to blowing up a balloon. At the beginning, there is no strain on the balloon, but as the balloon gets larger, the rubber becomes distorted and at some point can no longer hold together, so it bursts. A dielectric acts in a similar way. At some point in the voltage rise, the orbits will be so distorted that the material cannot hold together any longer, and it breaks down or punctures. The voltage necessary to cause this breakdown is called the *breakdown voltage*.

When a capacitor dielectric breaks down, the damage may be temporary or permanent, depending mostly upon the dielectric material itself. Some materials, such as paper or mica, become permanently damaged when punctured. A puncture in such a dielectric permits electricity to arc between the plates. This arcing causes the material to burn slightly near the puncture, so it is carbonized. Since carbon is a conductor of electricity, current may flow from one plate to the other, which means that the capacitor is practically short-circuited and must be replaced. On the other hand, capacitors with liquid or air dielectrics generally do not suffer permanent damage; the breakdown is only temporary, since the dielectric flows together again after the arcing has stopped. Such dielectrics are called *self-healing*.

Each material has a different potential at which it will break down or puncture, known as the *breakdown voltage*. Table B lists the approximate breakdown voltage of some dielectric materials for a thickness of one-thousandth of an inch.

TABLE B
DIELECTRIC BREAKDOWN VOLTAGES

<i>Dielectric</i>	<i>Breakdown voltage</i> (volts per 0.001 inch)
Air	20
Glass	335 to 2,000
Mica (clear India)	600 to 1,500
Paper	1,250 to 1,800
Porcelain	40 to 150
Quartz (fused)	200
Rubber (hard)	450

Voltage Ratings. Capacitors are rated for the voltage that may be safely applied to them. So, in selecting a capacitor, it is necessary to know not only the capacity but also the voltage of the circuit in which it is used. A typical paper (dielectric) capacitor has a rating of 0.1 μf at 600 WVDC (working volts d.c.), is designed to operate on 600 volts rms (effective) a.c. This means that it must be able to withstand a peak value of 1.41×600 volts or 846 volts in normal operation. The manufacturer must allow a safety factor, so such a capacitor must withstand a test voltage of 1,500 volts for from one to five seconds without damage.

15-8. CAPACITORS IN PARALLEL AND SERIES

Just as resistors may be connected in series and in parallel, capacitors are sometimes connected together to obtain certain values of capacitance. When capacitors are connected in parallel, the total capacity is equal to the sum of the individual capacities (as with resistance in series). For example, if three capacitors are connected in parallel, as shown in Fig. 15-14, where two capacitors each have a capacity of 2 μf and the third one has a capacity of 1 μf , the total capacity can be found by adding all three values together thusly:

$$\begin{aligned}
 C_t &= C_1 + C_2 + C_3 \\
 &= 2 + 2 + 1 \\
 &= 5 \mu\text{f}
 \end{aligned}$$

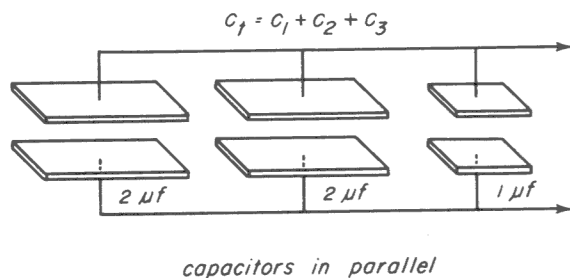
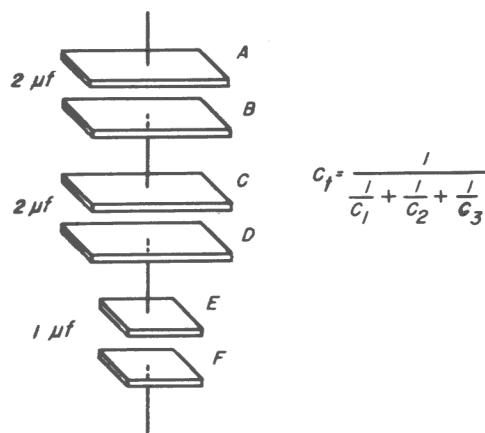


Fig. 15-14

You can see why this is so if you examine Fig. 15-14. Note that by connecting a capacitor in parallel, the total plate area is increased (over that of any one of the capacitors alone).

When capacitors are connected in series, the total capacity is *less* than the capacity of any one of the individual capacitors (just as with resistors connected in parallel). You can see why this is so if you examine the drawings in Fig. 15-15. The same capacitors that were used to illustrate capacitors connected in parallel are now connected in series, in Fig. 15-15a. Note that the plates are lettered A, B, C, D, E, and F. Plates B and C are connected together and so are electrically at the same point. Plates D and E also are electrically at the same point. So, it is possible to redraw these three capacitors in series by showing plates B and C and plates D and E directly touching each other, without connecting leads, as in Fig. 15-15b. The total capacity of the three series-connected capacitors is between the two end plates, A and F. The inner plates, BC and DE, serve to connect the layers of dielectric. We know that the capacity decreases as the distance between the plates (thickness of dielectric) increases. Therefore, the effective capacity of the three series-connected capacitors is less than the capacity of any one of the three capacitors separately. We will prove this a little later in this lesson. The formula for the total capacity of capacitors connected in series is like the formula for resistors connected in parallel:

$$C_t = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}} \quad \text{etc.}$$



capacitors in series

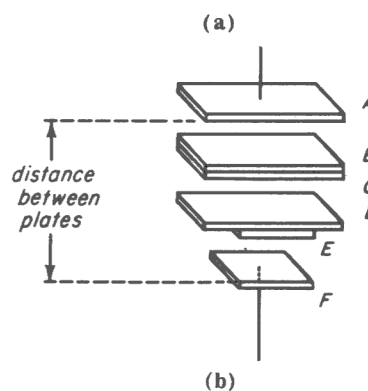


Fig. 15-15

Using the same capacitors that we connected in parallel in the previous example, we find:

$$\begin{aligned} C_t &= \frac{1}{\frac{1}{2} + \frac{1}{2} + \frac{1}{1}} \\ &= \frac{1}{0.5 + 0.5 + 1} \\ &= \frac{1}{2} \\ &= 0.5 \mu f \end{aligned}$$

If only two capacitors are connected in series, we can use the product-over-the-sum formula:

$$C_t = \frac{C_1 \times C_2}{C_1 + C_2}$$

For example two capacitors, one of $5\ \mu\text{f}$ and the other of $20\ \mu\text{f}$, connected in series have a total capacity of:

$$\begin{aligned}
 C_t &= \frac{C_1 \times C_2}{C_1 + C_2} \\
 &= \frac{5 \times 20}{5 + 20} \\
 &= \frac{100}{25} \\
 &= 4\ \mu\text{f}
 \end{aligned}$$

15-9. PRACTICAL CAPACITORS

A capacitor used in a radio or television circuit is selected with several characteristics in mind. Among these are:

1. Electrical size (capacity)
2. Physical size (how much room it will take up)
3. Working voltage (how many volts it can safely handle)
4. Type (fixed, variable)
5. Function (how it will be used)
6. Cost

There are other characteristics to consider, but these are the most important.

In general, capacitors are divided into two groups, *fixed* capacitors and *variable* capacitors. Fixed capacitors in turn, may be divided into *paper*, *mica*, *oil*, *ceramic*, and *electrolytic* types. Variable capacitors include *tuning*, *trimmer* and *padder* capacitors.

Paper Capacitors. Capacitors that use some form of waxed paper as a dielectric come in sizes from $0.001\ \mu\text{f}$ up to $8\ \mu\text{f}$, with voltage ratings of 100, 200, 400, 600, and 1,600 WVDC. The use of paper capacitors is generally limited to circuits of no higher

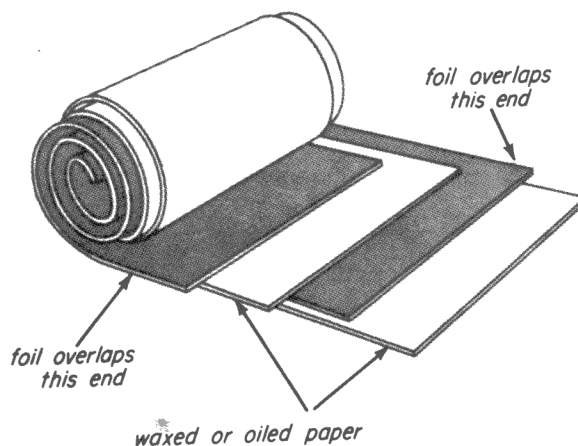


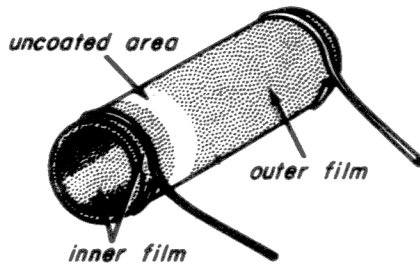
Fig. 15-16

than 600 volts rms. Paper capacitors are made from long, flat strips of metal foil (usually aluminum) separated by waxed paper strips. (Two or more very thin strips of paper are used, because even waxed paper has very small holes in the surface that might permit electrons to break through from plate to plate. However, it is unlikely that two or three sheets of paper would each have a hole all in a straight line from one plate to the

other.) The paper and foil sheets are usually rolled into a cylinder with the foil of one plate lapping over at one end of the roll and the foil of the other plate lapping over at the other end of the roll, as shown in Fig. 15-16. With the foil strips in rolls, the plates begin to look and act slightly like inductors. Such a capacitor tends to have inductance as well as capacitance. By lapping over and shorting all the turns together at the ends, the inductance is cancelled out, so paper capacitors that are made this way are called *noninductive* capacitors.

Mica Capacitors. Mica capacitors, as you know, are made from layers of metal foil separated by layers of mica. Mica capacitors, unless otherwise marked are rated at 500 WVDC. Some are made with a 300 WVDC rating, while others are made with 600-, 1,000-, 1,200-, 1,500-, 2,000-, 2,500-, and 3,000-volt ratings. They are made in capacities of from $5\ \mu\text{f}$ to $10,000\ \mu\text{f}$.

Oil Capacitors. Capacitors that use castor oil or some other oil as a dielectric are made in a way somewhat similar to the way in which paper capacitors are made. The



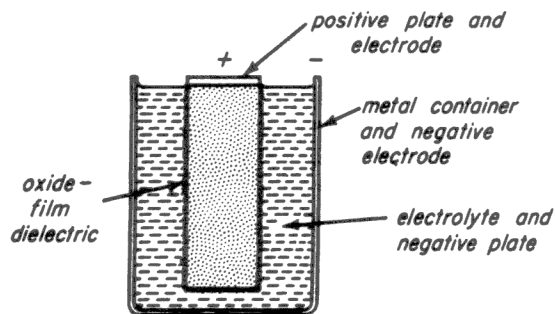
*inner film is brought outside
to make contact with lead*

Fig. 15-17

main difference between them and paper dielectric capacitors is that the plates are separated by oiled paper. They are normally made in capacities from $0.05 \mu\text{f}$ to $15 \mu\text{f}$ with voltage ratings of from 600 to 6,000 WVDC.

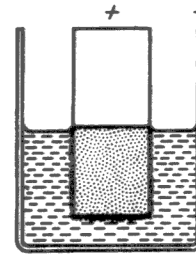
Ceramic Capacitors. Ceramic dielectric capacitors come in many physical sizes and shapes. They are usually made by depositing a metal film on the inner and outer surfaces of a ceramic tube. As shown in Fig. 15-17, the inner metal film is brought around one end to the outside in order to make contact with a wire lead. A small band of uncoated ceramic separates the two plates, as shown. An insulating coating is applied to the capacitor to protect the metal-film plates and to prevent shorting. Ceramic capacitors come in sizes from $1 \mu\text{f}$ to $10,000 \mu\text{f}$, with working voltages of from 1,000 to 30,000 volts.

Electrolytic Capacitors. High-capacity capacitors, such as those used in power-supply filtering, are usually of a type called *electrolytic* capacitors. The outstanding characteristic of these capacitors is large



simple electrolytic capacitor

Fig. 15-18



capacity decreases as electrolyte dries up

Fig. 15-19

capacity in a small-size unit. They differ so much from other capacitor types that it is necessary to explain the theory of their operation.

When you studied the primary cell, you learned that hydrogen bubbles form on the positive electrode. You found, too, that these bubbles form an insulating film between the electrode and the electrolyte and, as a result, the cell becomes polarized and current stops flowing. The same type of action occurs in an electrolytic capacitor. If two metal plates are placed in a borax solution and d.c. is connected to them, the current flow causes a film of oxide to form on the plate that is connected to the positive side of the d-c source. As soon as this oxide film covers the positive plate, current stops flowing. In such a capacitor arrangement, the positive plate is the metal sheet that receives the positive charge, the dielectric is the layer of oxide, and the electrolyte is the negative plate. The other metal plate acts only as a conductor and negative electrode. A basic electrolytic capacitor is shown in Fig. 15-18. The drawing shows that the positive plate is a sheet of aluminum, the dielectric is a film of oxide bubbles, the electrolyte is the negative plate, and the container (usually aluminum or copper) the negative electrode (making contact with the electrolyte.)

The main advantage of the electrolytic capacitor is that it has a dielectric that is self healing. If the film of oxide is pierced by a flow of electrons, other bubbles form as a result of the current flow and heal the area of the dielectric that is broken down.

Electrolytic capacitors are made in two types, *wet* and *dry*. A wet electrolytic is shown in Fig. 15-19. Wet electrolytic capaci-

tors remain good so long as the electrolyte does not dry up or spill. Remember that the capacity of a capacitor depends largely on the area of the positive and negative plates that face each other and face the dielectric. If half of the electrolyte dries up, as in Fig. 15-19, the negative plate area is reduced by fifty percent. If half of the positive plate is out of the electrolyte, only half of the positive plate is active. As a result, the capacity of the capacitor is cut in half. One disadvantage of a wet electrolytic is that it has to be mounted upright and remain that way if the fluid is not to spill out.

Most of the electrolytic capacitors used in radio and television receivers are of the dry electrolytic type. These are made from two aluminum sheets separated by gauze or blotting paper that has been moistened or been made wet with electrolyte. One of the aluminum sheets is made from thin, pure aluminum foil; this is the negative electrode. The other sheet is made from a heavier aluminum foil that has been *formed* by coating it with a thin layer of aluminum oxide. The electrolyte is basically the same as that used for wet electrolytic capacitors. However, something is added to the borax solution to make it more like a jelly or paste so that it becomes spill proof. In order to increase the area of the positive plate that is exposed to the electrolyte, the surface is sometimes etched — which means that the positive plate is given greater area by cutting up or roughing up the surface, as shown in Fig. 15-20. Because the electrolyte is the negative plate, this increases the capacity of the capacitor.

While these capacitors are called dry electrolytic capacitors, they must remain moist if they are to remain good. As soon as the electrolyte dries out, the capacitor loses most of its capacity and must be replaced by

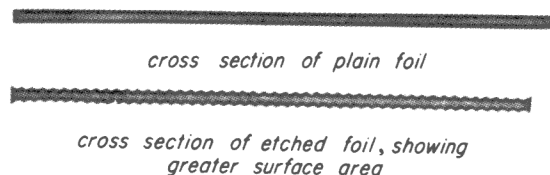


Fig. 15-20

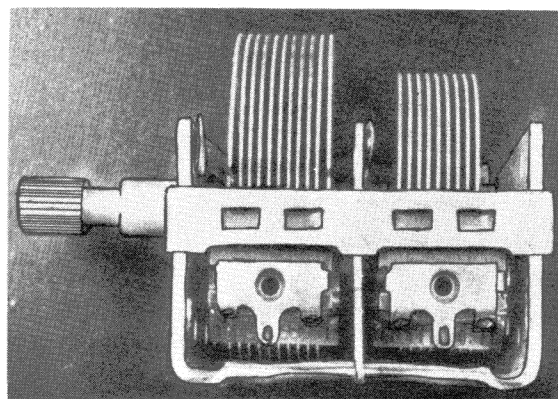


Fig. 15-21

a fresh one. In order to keep dry electrolytics moist, they must be well sealed against loss of moisture. Modern sealing compounds permit dry electrolytic capacitors to give long service without drying out.

Electrolytic Capacitor Ratings. Electrolytic capacitors are normally made in capacities from 1 to 6,000 μf , and in working voltages of from 10 volts to 600 volts. The very high capacity capacitors are made for low-voltage operation only. While electrolytic capacitors provide high capacity in a small space, compared to other capacitor types, they have a relatively high leakage current. In addition, the electrolytic capacitors used in radio and television receivers must always be connected with the correct polarity (marked on the capacitor), with the positive-voltage terminal connected to the positive capacitor plate, and the negative-voltage terminal connected to the negative capacitor electrode. When the polarity of the applied voltage is reversed, high current flows through the capacitor and the heated electrolyte usually causes the capacitor to burst. It is very important, therefore, to connect an electrolytic capacitor the right way the first time or risk ruining the capacitor.

Variable Capacitors. Up until now we have discussed fixed capacitors. However, few radio or television receivers could be made without variable capacitors in one form or another. The station-to-station tuning of most radio receivers is done with variable capacitors of many plates. Such capacitors are usually air-dielectric capacitors of the type shown in Fig. 15-21. They look compli-

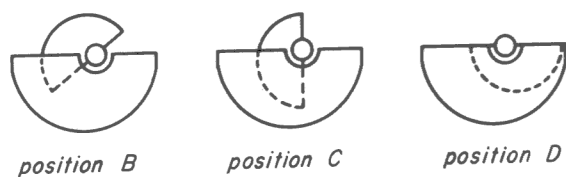
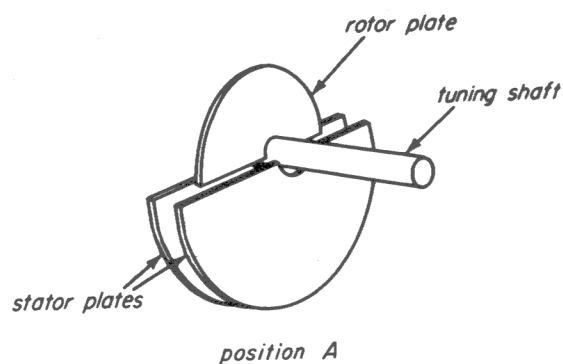
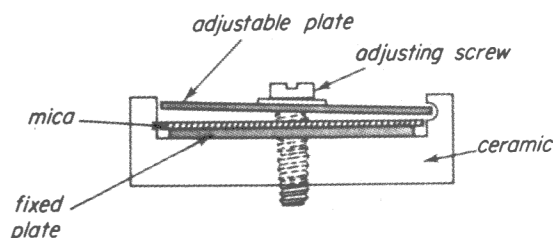


Fig. 15-22

cated, but are actually made from two sets of aluminum plates, one fixed and the other movable. The movable plates, called the *rotor* plates are attached to a shaft and move between the fixed (*stator*) plates to vary capacity. Figure 15-22 shows one rotor plate as it moves between two stator plates. In position A, the capacity is so very small that there is practically none at all. This is the minimum-capacity position. As more and more of the rotor plate enters between the stator plates, the capacity increases, until, when the plates are fully meshed (position D), the capacity is maximum.

The rotor turns on ball bearings (in most tuning capacitors) and is electrically connected to the frame of the capacitor. The stator, on the other hand, is insulated from the frame. So, in most applications, the frame and rotor are grounded. When two or more sections are made into the same variable capacitor, the rotor plates of each section are attached to the shaft, while the individual stator sections are insulated from the shaft and from each other.

The greater the number of plates, and the closer they are to each other when meshed, the greater is the capacity of the capacitor. Highly polished plates, free of dust, oxides, and other impurities, may be very close to each other without touching or shorting.



adjustable capacitor

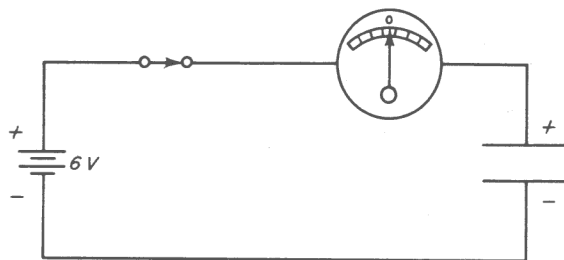
Fig. 15-23

There must be no wobble in the rotor plates as they rotate or they will short against the stator plates at different spots during the rotation.

Another type of variable capacitor is better called an *adjustable capacitor*. Such capacitors, as shown in Fig. 15-23, use mica as a dielectric. When the adjusting screw is turned in a clockwise direction, the plates are forced together, increasing the capacity. When the screw is turned counterclockwise, the plates separate and the capacity decreases. Such capacitors are used as *trimmer* or *padder* capacitors in tuning circuits. You'll learn more about them when you study r-f amplifiers and tuning circuits.

15-10. CAPACITANCE IN A-C CIRCUITS

Earlier in this lesson, we said that capacitance is the property of a circuit that opposes any change in voltage in the circuit. Let's see if this is really so. For a moment, we'll go back to charging a capacitor with a battery, as in Fig. 15-24. The drawing shows a capacitor charged by a 6-volt battery. The series ammeter shows no current flowing, so we know that the voltage across the capacitor plates is equal to the battery voltage. How-



capacitor is charged to six volts

Fig. 15-24

ever, let's change the battery to 7.5 volts. What will happen? The capacitor now has less voltage than the battery and is no longer fully charged. It opposes this change in the applied voltage by drawing current from the battery until it charges up to 7.5 volts, when it again is fully charged. On the other hand, if the battery voltage drops to 6 volts, the capacitor opposes the decrease in voltage by feeding current back through the battery until its voltage again equals the battery voltage. When the battery voltage rises, the capacitor opposes the rise but absorbs a greater charge; when the battery voltage decreases, the capacitor opposes the change by feeding current back into the circuit. The capacitor opposes a change in voltage at all times.

The capacitor opposes a change in voltage in much the same way as an inductance opposes a change in the amount of current flowing through it. Let us compare this opposition in inductive and capacitive circuits and see how similar it is. When current flows through an inductance, energy is stored in the magnetic field. If the current increases or decreases, the magnetic field will expand or contract, causing induced currents which oppose the change. Another way of stating this fact is to say that the coil stores energy in its magnetic field while the current increases, and sends energy back into the circuit when the current decreases. If the current stops flowing, the field collapses and its stored energy is used up as the coil tries to keep the current flowing. When voltage is applied to a capacitor, energy is stored in the form of an electric (electrostatic) field. You learned earlier in this lesson that the amount of charge increases or decreases depending upon the applied voltage. The capacitor tries to keep the voltage across its terminals constant by taking energy from the circuit (charging) when the voltage rises, and by feeding energy back (discharging) when the voltage falls. If the applied voltage falls to zero, the capacitor discharges, using up its stored energy trying to keep the voltage constant. This is just what happened when the inductance used its stored energy up trying to keep the current flowing in the circuit. So

we see that these two properties of circuits are very similar in that they store energy in their fields and use this energy to oppose current or voltage changes in the circuit.

When a.c. is applied to a capacitor, the voltage rises and falls all the time. While the voltage is rising, the capacitor charges and current flows into and charges the capacitor. When the applied voltage falls, the capacitor discharges and feeds current back into the line. The flow of current continues as long as a-c is applied to the capacitor. If we connected an a-c ammeter in series with the capacitor, it would measure this current. Capacitors are considered to pass a-c current, because current actually flows continuously in all parts of the circuit except through the dielectric between the plates. This property of capacitors that permits them to pass an alternating current is very important and is used in many ways in electronic circuits.

Capacitive Reactance. The opposition that a capacitor offers to the flow of alternating current is called *capacitive reactance*, abbreviated X_C , and, like X_L , it is measured in ohms. The amount of reactance depends on two factors: the capacity of the capacitor and the frequency of the applied voltage. We find the capacitive reactance by using this formula:

$$X_C = \frac{1}{2 \pi f C}$$

where:

X_C = capacitive reactance, in ohms

f = frequency in cycles per second

C = capacity in farads

Because capacities are often given in microfarads, we can change the formula to make it more useful in this way:

$$\begin{aligned}
 X_C &= \frac{10^6}{2 \pi fC} \\
 &= \frac{1,000,000}{6.28 fC} \\
 &= \frac{159,000}{fC}
 \end{aligned}$$

where:

X_C = capacitive reactance in ohms

f = frequency in cps

C = capacity in microfarads

Let's put the formula to work and see how it is used. Find the capacitive reactance of a 2- μ f capacitor when the frequency of the applied voltage is 60 cps:

$$\begin{aligned}
 X_C &= \frac{159,000}{fC} \\
 &= \frac{159,000}{60 \times 2} \\
 &= \frac{159,000}{120} \\
 &= 1,325 \text{ ohms}
 \end{aligned}$$

Let's try another. Find the capacitive reactance of a 1- μ f capacitor at the same frequency (60 cps):

$$\begin{aligned}
 X_C &= \frac{159,000}{60 \times 1} \\
 &= 2,650 \text{ ohms}
 \end{aligned}$$

Compare this result with the result in the last problem and you'll see that the lower the capacity of the capacitor (at the same frequency), the higher is the capacitive reactance.

If we know the capacitive reactance and the frequency, we can find the capacity by changing the formula around like this:

$$C = \frac{159,000}{f X_C}$$

For example, we know that the capacitive reactance of a 2- μ f capacitor is 1,325 ohms and that the reactance of a 1- μ f capacitor is 2,650 ohms. Let's find the capacity of two 2- μ f and one 1- μ f capacitors connected in series. Capacitive reactances, like resistances in series, add one to the other. So:

$$\begin{aligned}
 X_{Ct} &= 1,325 + 1,325 + 2,650 \\
 &= 5,300 \text{ ohms}
 \end{aligned}$$

$$C = \frac{159,000}{60 \times 5,300}$$

$$= \frac{159,000}{318,000}$$

$$= 1/2 \text{ or } 0.5 \mu\text{f}$$

This is the same answer that we received when we first did this problem on page 13, which proves the rule for finding the total capacity of capacitors connected in series.

Phase Angle. You have already learned that the phase angle is the *difference in degrees* between the time when two sine waves pass the zero axis, going in a positive direction. In inductive circuits, you saw that the current lags the applied voltage. Just the opposite is true in a capacitive circuit; the current leads the applied voltage by 90-degrees. We will use Fig. 15-25 to show why this is so. This figure shows how the current I_C through a capacitor varies.

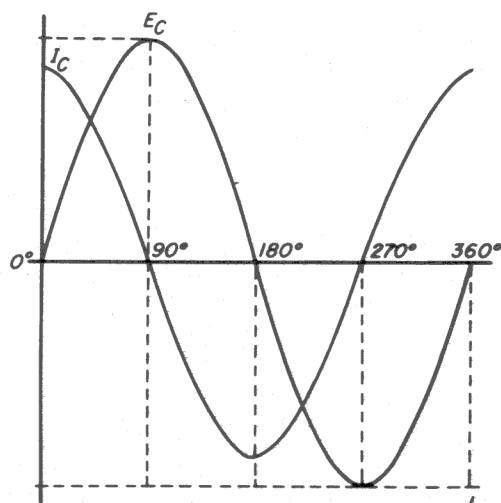


Fig. 15-25

during one cycle of an applied voltage E_C . Remember, this current flow is the charging current which flows to the negative plate when the capacitor charges, and in the opposite direction when it discharges. In Fig. 15-25, the capacitor is shown charging up from 0° to 90° and from 180° to 270° . The voltage across the capacitor is increasing during these intervals, first in the positive direction; then in the negative direction, but it is still increasing. Examine the interval from 0° to 90° . As the capacitor charges, that is, as the voltage across it *increases*, the current flowing *decreases*. When the capacitor voltage reaches its maximum, the current is at zero. In the interval from 90° to 180° , the capacitor is discharging, with the current rising to a maximum (in the negative direction) as the capacitor voltage falls to zero. From 180° to 270° , the capacitor charges up again (now in the negative direction) until at 270° it is fully charged and the current is again at zero. Thus, you see that the current flow is maximum when the applied voltage is changing at the fastest rate. Throughout the cycle, the current is 90° ahead of the applied voltage.

In order to keep track of leading and lagging currents, there are two little words that will help you remember. In an inductive circuit, the voltage leads the current. To remember this, think of the word *ELI* (the voltage *E* in an inductive circuit *L* comes before the current *I*.) In a capacitive circuit, the current leads the voltage (the voltage

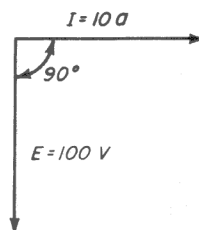


Fig. 15-26

lags the current). To remember this, think of the word *ICE* (the current *I* in a capacitive circuit *C* is ahead of the voltage *E*).

Just as in inductive circuits, we can show phase angle, (the number of degrees by which the current leads the voltage) by means of a vector diagram. Fig. 15-26 shows the 90° -degree phase angle between current and voltage in a capacitive circuit. This vector diagram shows a current of 10 amperes flowing through a capacitor in a series circuit. The vector representing current is in the zero-degree position. This is done for convenience, because the same current flows through all parts of a series circuit. Since we assume that vectors rotate in a counterclockwise direction, and that the current always leads the voltage in a capacitor, the vector representing the voltage drop is drawn 90° behind the current vector. The vector diagram (Fig. 15-26) shows a current of 10 $\angle 0^\circ$ amperes flowing through a capacitor, causing a voltage drop of 100 $\angle -90^\circ$ volts.

Resistance and Capacitance. Unlike inductors, most capacitors have so very little resistance, except at very high frequencies, that we can think of them as offering only reactance to a circuit. Electrolytic capacitors, with their high leakage, are the most important exception; in calculations that include electrolytic capacitors, leakage resistance is a very important factor.

However, in a series circuit containing resistance and capacitance, the current flow will lead the applied voltage by *less* than 90° -degrees. The effect of the resistance is to reduce the angle by which the current leads the applied voltage. For example, if the amount of resistance is equal to the amount of capacitive reactance, the current

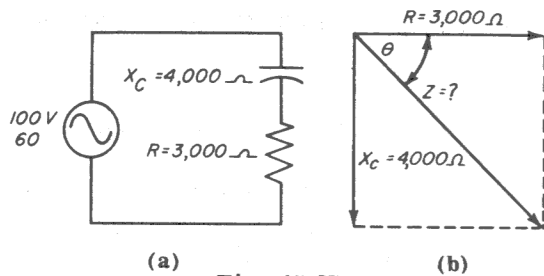


Fig. 15-27

will lead the applied voltage by only 45 degrees.

Fig. 15-27a shows a 100-volt 60-cycle generator connected to a series circuit, consisting of a resistor of 3,000 ohms and a capacitor whose reactance is 4,000 ohms at 60 cycles. To find the current that flows in this circuit, we must first find the impedance. The impedance is the *vectorial sum* of the resistance and reactance, and is found by the same method you used to find impedance in inductive circuits. In Fig. 15-27b the vectors representing resistance and reactance are drawn 90-degrees apart. The resistance vector is drawn in the zero-degree position and the capacitive reactance X_C vector in the -90 -degree position. The impedance depends on the relative sizes of the resistance and the reactance and is shown by the vector marked Z in the diagram. If there were little or no reactance, the impedance vector would be close to the resistance vector and the phase angle would be small. If there were little or no resistance, the impedance vector would be close to the reactance vector and the phase angle would be closer to 90-degrees.

The Z vector is the hypotenuse of the right triangle, so the same formula that you used for series resistance and inductive reactance applies:

$$Z = \sqrt{R^2 + X_C^2}$$

where:

Z = impedance in ohms (at the frequency used to find X_C)

R = resistance in ohms

X_C = capacitive reactance in ohms (at the generator frequency)

Using this formula to solve for Z in Fig. 15-27b, we find:

$$\begin{aligned} Z &= \sqrt{3,000^2 + 4,000^2} \\ &= \sqrt{9,000,000 + 16,000,000} \\ &= \sqrt{25,000,000} \\ &= 5,000 \text{ ohms} \end{aligned}$$

Now we can find the amount of current flow using ohms law for a.c. circuits:

$$\begin{aligned} I &= \frac{E}{Z} \\ &= \frac{100}{5,000} \\ &= 0.02 \text{ ampere} \end{aligned}$$

This current flows through the resistance and the capacitor. The voltage drop across the resistor E_R and the voltage drop across the capacitor E_{X_C} can also be found by using ohms law for a.c. circuits as follows:

$$\begin{aligned} E_R &= IR \\ &= 0.02 \times 3,000 \\ &= 60 \text{ volts} \\ E_{X_C} &= IX_C \\ &= 0.02 \times 4,000 \\ &= 80 \text{ volts} \end{aligned}$$

You learned that the sum of the voltage drops in a series circuit must equal the applied voltage, but here the sum of 60 and 80 is 140 volts, and you know that the applied voltage is only 100 volts. The sum of the applied voltages will equal 100 volts if they are added vectorially as shown in Fig. 15-28. There are three voltages in the circuit and one current. Since this current is common to all components as explained previously, it is shown in the zero-degree position. The voltage drop across the resistor is in phase with the current so it is shown on the same line. The current leads the applied voltage by the angle marked θ which will be discussed in the next section of this lesson.

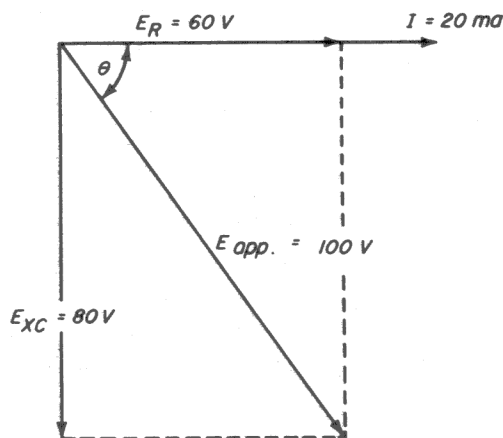


Fig. 15-28

The voltage across the capacitor is 90-degrees behind the current through the capacitor. Notice that the voltage drop across the capacitor is *always* 90-degrees behind the current through it, though this current may lead the applied voltage by *less* than 90-degrees. The next section of this lesson will tell how to find the amount of lead.

Finding the Phase Angle. Up until now, we have been speaking of angles of 90 and 0 degrees. However, it is often necessary to know the angle of lead or lag of a voltage when the angle lies between 0 and 90 degrees. The symbol for the angle of lead (or lag) is the Greek letter θ (pronounced thay-ta). So, when we speak of angle θ , we mean the phase angle. Table C lists the angles, in 1-degree steps from 0 degrees to 90 degrees. Each angle is followed, in the table, by a 4-place decimal fraction. This decimal fraction is called the *cosine* of the angle. Here is how we use this table. First we find the cosine, which is equal to the resistance divided by the impedance, or:

$$\begin{aligned} \text{cosine } \theta &= \frac{R}{Z} \\ &= \frac{3,000}{5,000} \\ &= 0.6000 \end{aligned}$$

For example, in this last problem, the resistance was 3,000 ohms and the impedance was 5,000 ohms. So, we find the cosine in this way:

TABLE C - ANGLES AND COSINES

Angle	Cosine	Angle	Cosine	Angle	Cosine
0	1.0000	30	0.8660	60	0.5000
1	0.9998	31	0.8572	61	0.4848
2	0.9994	32	0.8480	62	0.4695
3	0.9986	33	0.8387	63	0.4540
4	0.9976	34	0.8290	64	0.4384
5	0.9962	35	0.8192	65	0.4226
6	0.9945	36	0.8090	66	0.4067
7	0.9925	37	0.7986	67	0.3907
8	0.9903	38	0.7880	68	0.3746
9	0.9877	39	0.7771	69	0.3584
10	0.9848	40	0.7660	70	0.3420
11	0.9816	41	0.7547	71	0.3256
12	0.9781	42	0.7431	72	0.3090
13	0.9744	43	0.7314	73	0.2924
14	0.9703	44	0.7193	74	0.2756
15	0.9659	45	0.7071	75	0.2588
16	0.9613	46	0.6947	76	0.2419
17	0.9563	47	0.6820	77	0.2250
18	0.9511	48	0.6691	78	0.2079
19	0.9455	49	0.6561	79	0.1908
20	0.9397	50	0.6428	80	0.1736
21	0.9336	51	0.6293	81	0.1564
22	0.9272	52	0.6157	82	0.1392
23	0.9205	53	0.6018	83	0.1219
24	0.9135	54	0.5878	84	0.1045
25	0.9063	55	0.5736	85	0.0872
26	0.8988	56	0.5592	86	0.0698
27	0.8910	57	0.5446	87	0.0523
28	0.8829	58	0.5299	88	0.0349
29	0.8746	59	0.5150	89	0.0175
				90	0.0000

Next we look for this decimal fraction in the table and find that the nearest value to 0.6000 is shown in the table as 0.6018. We find that this is the cosine of an angle of 53 degrees. So the phase angle (θ) is 53 degrees. Because the voltage lags the current the angle is shown as a negative angle, so the applied voltage could be represented by $E_{app} = 100 \angle -53^\circ$. The impedance $Z = 5,000 \angle -53^\circ$.